Monitoring and Reducing Exposure of Infants to Pollutants in House Dust

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Contents

1 Introduction

Babies come with great potential but great vulnerability. It is estimated that infants eat twice as much dust (100 mg vs. 50 mg/d), weigh one sixth as much, and are up to ten times more vulnerable than are adults to dust exposure (U.S. EPA 2002,

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2003). The developing neurological, immune, digestive, and other bodily systems of infants are easily affected at low doses and these systems are less able to metabolize, detoxify, and excrete pollutants (Grandjean and Landrigan 2006; U.S. EPA 1996, 2002, 2003). Up to 11% of toddlers may exhibit pica behavior, eating nonfood items, and may consume up to 10 g of soil and dust per day (Calabrese and Stanek 1991; Mahaffey and Annest 1985). The time of life when exposure occurs may be as important as the dose (Grandjean and Landrigan 2006; Louis et al. 2007). Infants breathe more air, drink and eat more relative to their body weight, and engage in risky behaviors such as mouthing hands, toys, furniture, and other nonfood items. They crawl on floors, where they are in close proximity to carpets, and may breathe higher levels of dust (Rodes et al. 1996). Exposures early in life may trigger sensitization leading to development of chronic diseases such as asthma or predispose to cancer that takes decades to develop (Louis et al. 2007).

Childhood chronic health conditions that limited daily activity by at least 3 mon each year increased from 1.8% in 1960 to 7% in 2004. Changes in physical and social environmental exposures may be a significant cause of this rapid rise (Perrin et al. 2007). The leading chronic diseases of children are asthma, which has increased sharply in the last 30 yr; attention deficit hyperactivity disorder (ADHD), which now affects around 6% of school age children; and obesity, which increased from 5% in 1971–1974 to 18% of children and adolescents in 2002 (Perrin et al. 2007). Not all children with these diseases have physical activity limitations lasting at least 3 mon each year, and therefore are not included in the 7% of children with such conditions. This increase in children's chronic disease has sobering implications for future health costs, school achievement, and work productivity. Krieger et al. (2005) and Takaro et al. (2004) suggest that morbidity from moderate and severe (poorly controlled) asthma can be reduced by 50% or more by reducing exposure to triggers in the home. Braun et al. (2006) suggest that reducing the lead exposure of babies may reduce ADHD. Exposure to neurotoxic chemicals is associated with ADHD, neurodevelopment disorders, autism, loss of intelligence, and mental retardation (Grandjean and Landrigan 2006).

Research suggests that house dust is the main source of infant exposure to allergens (Pope et al. 1993), lead (Davies et al. 1990; Lanphear 1996; Lanphear et al. 2005; U.S. EPA 1997) and polybrominated diphenyl ethers (PBDEs) (Jones-Otazo et al. 2005; Stapleton et al. 2005; Wu et al. 2007). Dust is also a major in-home exposure source for pesticides, polyaromatic hydrocarbons (PAHs), phthalates, endocrine disrupting compounds (EDCs), arsenic, cadmium, chromium, mold, endotoxin, and bacteria (Benson 1985; Butte and Heinzow 2002; Camann et al. 2002a; Lioy 2006; Rasmussen et al. 2001; Roberts et al. 1999; Rudel et al. 2003). The track-in or inside generation of animal feces, hair, and saliva provides a source of viruses, gram-negative bacteria, and endotoxin in dust (Benson 1985; McCaustland et al. 1982). Franke et al. (1997) and Roberts and Ott (2006) suggest that floor dust is a source of indoor air exposure to particles, gram-negative bacteria, volatile organic compounds, and mold. Over 100 potentially toxic metals, pesticides, other carcinogens, other neurotoxins, allergens, and EDCs have been identified in house dust (Butte and Heinzow 2002; Lioy 2006; Papadopoulos 1998; Rudel et al. 2003).

House dust contains many mutagens including direct mutagens that do not require metabolic activation (Roberts et al. 1987; Maertens et al. 2004). Maertens et al. (2008a, b) estimate that 25% of the mutagenic activity in house dust comes from PAHs. The combined risk from this mixture of pollutants in dust is unknown (Menzie et al. 2007).

The fine particles produced by combustion tend to combine with the larger particles found in soil and house dust (Lewis et al. 1999). Soil particles greater than 2 μm in diameter are preferentially tracked into homes. Contaminants adhering to such particles include metals, pesticides, PAHs, and soot (Chuang et al. 1999; Roberts et al. 1996). Dust and soil particles smaller than 100–200 μm in diameter may adhere to skin, clothing, and other objects and may be ingested through mouthing. Smaller particles (e.g., with diameters of ~2–20 μm) may be resuspended into air, where they can be breathed into the upper respiratory system and lungs (Micallef et al. 1998; Thatcher and Layton 1995). Particles less than 10 μm in diameter are inhalable and have a higher surface area per unit mass, which increases their inhalation toxicity. The concentrations of pesticides and PAHs in house dust are much higher on inhalable and respirable particles than on larger particles (Lewis et al. 1999).

Indoor pollution was ranked by the U.S. EPA as a high environmental risk 20 yr ago (GAO 1999; U.S. EPA 1987, 1990). The pollutants in house dust are an important component of indoor pollution. Meaningful progress has been made in monitoring and reducing lead dust exposure. Pollution monitoring and exposure analysis are required for efficient management of health risks and costs (Berube 2007a, b; Ott 2006). Recent research suggests that an economic analysis should be performed on the benefits of measuring and controlling the exposure of babies to all toxic compounds in house dust (Grandjean and Landrigan 2006; Lanphear et al. 2005; Louis et al. 2007; Maertens et al. 2008b; Roberts and Ott 2006).

The purpose of this article is to review and analyze the literature on monitoring and reduction of infant exposures to pollutants in house dust. We deal briefly with monitoring methods. We discuss concentrations in dust of a large variety of compounds including metals and persistent organic pollutants. We discuss methods of cleaning and ways to reduce exposure, particularly by home visits of trained volunteers. We conclude by suggesting hypotheses for further research related to cleaning and reduction of exposure by home visits.

2 Monitoring Pollutants in Surface and Deep Dust

Pollutants may be measured in environmental media (air, food, water, dust) and biological media (exhaled breath, blood, urine, hair, saliva). For the persistent pollutants of interest here, dust is a preferred sampling medium. Many pollutants have low vapor pressures and preferentially accumulate in dust, soil, or food. However, concentrations are generally higher in dust than in soil or food (U.S. EPA 2007).

Also, dust concentrations and loadings of pollutants show less variation over time than do air or urine concentrations (Egeghy et al. 2005).

2.1 Monitoring Methods

Measurement of dust levels on bare surfaces and in carpets is required to evaluate risks and control exposures. The concentration of pollutants in house dust (expressed as μg/g) can be measured by several methods including simply collecting and analyzing used vacuum cleaner bags from home (Colt et al. 1998). The dust loading on the surface of a carpet (in g/m^2) can be measured by weighing upright vacuum cleaner bags before and after vacuuming measured areas of a carpet eight times (Roberts et al. 1991b). However, it is difficult to compare such data collected with different vacuum cleaners, avoid cross contamination between samples, and extract small particles from the bag fabric.

Cassette samplers, rollers, wet wipes, and many other methods have been used to measure pollutant concentrations in house dust and in dislodgeable residues from carpets and upholstery (Farfel et al. 1994; Lanphear et al. 1995; Lioy et al. 1993; Hee et al. 1985; Roberts et al. 1991c; U.S. EPA 1989, 1995, 1996b). These methods will not be described here, but comprehensive reviews on them have been published by Lewis (2005), Lioy (2006), Pope et al. (1993), and the U.S. EPA (1997, 2007).

In 2001, the U.S. EPA developed a standard wipe method for measuring lead (Pb) loading on bare and carpeted surfaces. A standard of 40 μg Pb/ft^2 was established to protect small children, and this value has been used as a threshold for granting approval to rehabit old homes, after lead remediation or remodeling. Lead loading in carpet is among the best predictors of expected lead levels in blood of exposed toddlers (Davies et al. 1990). Moreover, carpet loading (μg of Pb/m^2) of pollutants correlates better with resuspended pollutant levels generated from activity on the carpet than does pollutant concentration (μg of Pb/g) (Lewis 2002; Roberts and Ott 2006).

A high-volume small-surface sampler (HVS3) described in ASTM International Standard Method D5438 (ASTM, 2007) was developed for the U.S. EPA in 1990 to assess risk from lead, pesticides, PAHs, and other pollutants in house dust on bare surfaces and carpets (Roberts et al. 1991a, c). The HVS3 allowed measurement of both concentration (μg/g) and loading (μg/m^2) of surface dust pollutants by using a cyclone and by controlling air flow and pressure drop across the nozzle. The cyclone allows collection of a large sample (up to 100 g) without any reduction in air flow. In 2002, the HVS3 was simplified to create the HVS4, which is less costly and easier to use and transport (Roberts et al. 2004). Several studies designed to measure children's exposure to pollutants (pesticides, lead, allergens, and PAHs) have used the HVS3 or HVS4 units (Roberts et al. 1999, 2004; U.S. EPA 2000; McCauley et al. 2001; Fenske et al. 2002; Bradman et al. 2007). One study compared HVS3 results to those using household vacuum cleaner bags and found little difference (Colt et al. 2008). Because the household vacuum cleaner bags presumably represented sample material collected over a long term than did the HVS3 samples, this provides further evidence that dust constitutes a stable matrix for pesticides.

2.2 *Metals*

Elements (metals) have been monitored in house dust in several studies since the 1990s (Rasmussen et al. 2001; Siefert et al. 2000). Examples of concentrations from a recent study in 78 California classrooms are shown in Table 1. Also shown in Table 1 are the U.S. EPA Region IX (which includes California) Preliminary Remediation Goals (PRGs) for 24 toxic elements in residential soils (Smucker 2004). These PRGs were selected, in part, to protect the health of infants. Exceeding these PRGs in residential soil at a Superfund site triggers a risk assessment, and these same PRGs may be used as standards for cleanup. The PRG values are usually set to provide an added margin of safety for cancer risk of less than one in one million, although cleanup standards may also be set for cancer risk rates of 1 in 100,000, or 1 in 10,000. The concentration of one toxic metal – arsenic – exceeded the PRG for the cancer endpoint in California classrooms.

Table 1 Metal concentrations (μg/g) in dust samples from California classrooms (N = 78)

Element	Preliminary remediation goals[a]	California classrooms[b]	
		Median	95th Percentile
Aluminum	76,000	47,500	60,100
Arsenic[c]	0.38 or 22	11.6	17.3
Cadmium	37	3.55	13.3
Cesium		0.24	0.70
Chromium	210	33.1	72.8
Cobalt	4,700	1.7	14
Copper	2,900	60.2	288
Iron	22,000	22,300	37,300
Lead	400	61.6	190
Magnesium		8,700	14,300
Manganese	1,800	316	417
Nickel	1,600	33.2	83.2
Palladium			4.03
Selenium	390	1.56	13.5
Strontium	47,000	139	235
Titanium	310,000	320	877
Vanadium	550	40	65
Zinc	23,000	980	2,020

[a] For residential soils, in ppm (Smucker 2004)
[b] CARB (2003)
[c] Arsenic PRG = 0.38 ppm for cancer endpoint, 22 ppm for noncancer

Toxicants may become concentrated in house dust reservoirs. The concentration of toxic metals in house dust may be from 2 to 32 times higher than the levels found in garden soil around the house (Rasmussen et al. 2001). The median concentration of mercury in house dust (1.61 μg/g) was 32 times that found in an Ottawa garden soil; this suggests that an indoor source of mercury also may exist. Moreover, the type of heat source used in houses affected mercury concentrations found in dust: electric (4.13 μg/g), gas (1.36 μg/g), and oil (1.39 μg/g). Mercury switches are one possible contamination source in homes utilizing such switches in electric heaters. However, it is difficult to pin exact sources down, because a wide variation in metal concentrations exists from one house to another and in the ratio of indoor to outdoor concentrations. There is a strong correlation between metal levels and concentrations of organic carbon in house dust (Rasmussen et al. 2001; Rasmussen 2004). The higher organic carbon content of urban fine house dust (27.5%), in relation to topsoil (4%), for particles less than 53 μm in diameter, may be one factor that increases indoor dust toxicity (Rasmussen 2004). However, metal concentrations in indoor dust cannot be predicted from outdoor soil levels (Rasmussen et al. 2001; Rasmussen 2004). The highest children's blood lead levels and lead loadings in carpets are associated with the following factors: home remodeling, paint removal, lack of an effective vacuum cleaner, infrequent cleaning, and peeling paint inside and outside of older houses (Davies et al. 1990; Roberts et al. 1991b, 1999, 2004; U.S. EPA 1997). Some research suggests that lead dust ingestion in young children may account for 1,000 times more exposure than inhalation (Roberts and Dickey 1995).

Egeghy et al. (2005) found that a single measurement of lead in blood or chlorpyrifos in house dust was sufficient for an estimate of average resident exposure. However, most other compound/media combinations required more measurements. Egeghy concluded that measurements in both biological fluids and dust were more consistent than those in indoor air.

U.S. EPA action to remove lead from U.S. gasoline resulted in a dramatic decline of lead levels in children's blood from 1976 to 1999. During this period, the median blood lead levels of children aged 5 and under dropped from 15 to 2.2 μg Pb/dl (U.S. EPA 2003). This reduction shows the potential of product reformulation for protecting children. However, one in three children, under the age of 6 yr, still live in older houses that retain a lead-based paint hazard (Clickner et al. 2001). Some 51% of 154 Seattle homes of Master Home Environmentalist (MHE) volunteers built before 1940 had house dust lead levels that exceeded the U.S. EPA PRGs of 400 μg/g (Roberts and Ott 2006; Smucker 2004).

2.3 Pesticides

Carpeting is a common dust reservoir and an efficient pesticide concentrator. Carpets collect soil particles tracked in from outdoors and collect settled dust from indoor air. Carpet-embedded dust, carpet fibers, backing, and padding can also absorb pesticides from liquid and aerosol sprays, gaseous pesticides in air within the home, or from vapors that intrude into the home from the crawlspace or basement. Typically, pesticide concentrations in vacuumable house dust are 10–100 times higher than those found in outdoor surface soil (Lewis et al. 1994; Simcox et al. 1995). Pesticide residues may persist for years in carpets, where they are protected from sunlight, rain, temperature extremes, and some microbial action.

Even if residents do not use indoor pesticides, track-in of lawn-applied pesticides can be of particular concern. The presence in house dust and indoor air of the herbicide 2,4-dichlorophenoxyacetic acid (2,4-D), the insecticide carbaryl, and the fungicide chlorothalonil, which are normally applied exclusively outside the home, implies that the pollutants have been transported from outdoors (Lewis et al. 1999).

An important community of interest for pesticide exposure is farmworkers, particularly migrant farmworkers, who may have children at greatly increased risk of exposure to pesticides transported into the home as residues on clothes or shoes. Several studies have focused on farmworker-family exposures to pesticides in house dust (Bradman et al. 2007; Freeman et al. 2004; Arcury et al. 2006; McCauley et al. 2001; Fenske et al. 2002; Thompson et al. 2008; Ward et al. 2006). Most of these studies found elevated levels in house dust and/or in urinary metabolites of the targeted agricultural pesticides.

U.S. EPA studies have shown that walking over pesticide-treated turf, as long as 1 wk after treatment, can result in transfer of residues to carpet dust in amounts proportional (3–4%) to the dislodgeable residues on the turf (Nishioka et al. 1996). Results from these studies indicated that 2,4-D residues, in the home from lawn applications, were measurably higher with active children and pets (Nishioka et al. 1999, 2001). Concentrations ($\mu g/m^3$) measured on 10-μm airborne particles were two to ten times higher than those on 2.5-μm particles, with concentrations declining on particles larger than 10 μm. Indoor residues persisted after lawn residues had dissipated.

A recent report (U.S. EPA 2007) has reviewed 13 studies, all carried out by the EPA between 1997 and 2001. Because the EPA report is both recent and quite complete, we will not repeat its findings here. Readers are encouraged to check this report both for the results of the reviewed studies, five of which involved more than 100 children each, and for a comparison of the many dust sampling methods employed in these studies.

The potential for exposure by ingestion versus inhalation depends on pesticide volatility. The primary route of exposure for infants and toddlers, who are often in close contact with the floor, is ingestion of either contaminated house dust or surface residues; intake of nonvolatile pesticides such as pyrethroids that are both abundant in carpet dust and widely used indoors and herbicides tracked in from lawns is a prominent source of such exposure (Lewis et al. 1999; Rudel et al. 2003; U.S. EPA 2000). For relatively volatile pesticides and those adhering to respirable particles inhalation may represent the primary exposure route. To illustrate this point, the authors of one study (Lewis et al. 2001) estimated that a young child's potential indoor exposure to diazinon (now cancelled for residential use) may be 50 times greater from inhalation than from ingestion of house dust at 100 mg/d [EPA's exposure guideline for infants and toddlers; U.S. EPA (1996a, 2002)].

Alternatively, ingestion by mouthing of diazinon residues on the hands of the children who participated in this study would have exceeded the inhalation exposure level by 2- to 3-fold.

Residues from pesticides discontinued long ago in the USA are still found in house dust. Chlordane (banned in 1988) was still detected in 38% of homes, whereas DDT (discontinued in 1972) was still found in 70% of house dust samples collected from 1998 to 2001 (Colt et al. 2004). The lower volatilities of DDT, DDE, carbaryl, and methoxychlor suggest that they will persist longer in house dust because lower amounts vaporize at ambient temperatures. Pesticides with higher vapor pressures may condense closer to the point of application in the winter and translocate to cooler climates in the summer, in a gas chromatographic or “grasshopper” effect (Riseborough 1990; Lioy 2006). Persistent pesticides with low vapor pressures may be transported long distances by foot and vehicular traffic, and on airborne fine particles, even to pristine snow-covered areas in the Western National Parks (Hageman et al. 2006; Kurtz 1990; Lewis and Lee 1976; Lewis et al. 1994, 1999; Lewis 2005; McConnell et al. 1998; Simcox et al. 1995).

In the USA, home use of common pesticides increased from 36 million kg (of active ingredients) in 1999 to 46 million kg in 2001; lawn-applied herbicides accounted for 71% of the total (U.S. EPA 2004). Not included in these figures are 27 million kg of nonconventional pesticides such as disinfectants, deodorizers, and insect repellants. Although accurate assessment of total exposure risks associated with pesticide use in and around the home remains difficult, it is clear that residents may be exposed to pesticide residues in untreated as well as treated areas of the home, and children may be exposed through intimate contact with both intentionally and incidentally contaminated surfaces.

2.4 PAHs and PCBs

Carpets are contaminated by and accumulate PAHs as well as pesticides. Table 2 presents the concentration distributions of prevalent pesticides, PAH, and PCB (polychlorinated biphenyl) congeners in house dust from subjects enrolled in a population-based case-control study of non-Hodgkins lymphoma (NHL), a large study in which semivolatile organic chemicals were measured in dust to investigate purported risk factors for NHL. Vacuum cleaner bag dust was analyzed if subjects had used their vacuum cleaner within the previous year and had owned at least half of their carpets for 5 yr or more. The median length of residence in homes was 20 yr for both cases and controls. Results indicated that NHL risk was elevated by 50% if any PCB congeners were detected; greater risk existed at higher PCB concentrations in dust, and there was evidence of greater effects for PCB 180 (Colt et al. 2005). NHL risk in men was elevated by 30%, if DDE was detected. Chlordane treatment of homes for termites elevated the resident’s NHL risk by 30%, and NHL risk increased with increasing levels of chlordane in house dust (Colt et al. 2005, 2006). The only chemicals in dust found to elevate NHL risk had been banned for

Table 2 Concentration distributions of prevalent pesticides, polycyclic aromatic hydrocarbons (PAHs), and polychlorinated biphenyl (PCB) congeners in house dust collected from 616 homes in Detroit, MI, Los Angeles County, CA, Seattle, WA, and the State of Iowa, 1999–2001 and from 78 California classrooms

			House dust[b]			Classroom dust[c]		
Pollutant	Preliminary remediation goals[a] (μg/g)	% Detected	Median (μg/g)	95th Percentile (μg/g)	Vapor pressure (kPa at [ ]°C)	% Detected	Median (μg/g)	95th Percentile (μg/g)
Pesticide								
Carbaryl	6,100	35	0.050	3.01	4.1×10^{-8} [25][c]			
Chlordane	1.6	38	0.021	0.44	1.3×10^{-6} [25][c]			
Chlorpyrifos	180	68	0.108	3.53	2.7×10^{-6} [25][d]	97	0.308	1.906
2,4-D		78	0.30	7.01				
DDE	1,7	46	0.0237	0.20	4.2×10^{-7} [20][e]	54	0.008	0.052
DDT	1.7	70	0.09	1.6	2.5×10^{-8} [20][d]			
Diazinon	55	39	0.025	0.76	1.2×10^{-5} [25][d]	58	0.035	0.679
Methoxychlor	310	42	0.074	2.07	1.1×10^{-7} [25][f]			
Pentachlorophenol		87	0.37	3.18				
cis-Permethrin		72	0.33	20.9	2.5×10^{-9} [20][d]	99	0.256	1.870
trans-Permethrin		74	0.70	38.7	1.5×10^{-9} [20][d]	100	0.320	2.329
ortho-Phenylphenol		99	0.25	1.25	1.5×10^{-4} [25][h]	100	0.063	0.486
Propoxur		77	0.072	1.45	1.3×10^{-6} [20][d]			
PAHs								
Benz(*a*)anthracene	0.62	98	0.136	1.79	4.1×10^{-9} [25][h]	79	0.053	0.329
Benzo(*b*)fluoranthene	0.62	99	0.31	3.95	5.0×10^{-10} [25][h]			
Benzo(*k*)fluoranthene	6.2	91	0.099	1.10	5.2×10^{-11} [25][h]	80	0.057	0.378
Benzo(*a*)pyrene	0.06	96	0.154	2.39	3.0×10^{-10} [25][h]	59	0.054	0.306
Chrysene	62	99	0.27	2.84	4.0×10^{-9} [25][h]	93	0.149	0.678
Dibenz(*a*,*h*)anthracene	0.06	71	0.036	0.50	1.3×10^{-11} [25][h]	41	0.003	0.081
Indeno(1,2,3-*cd*)pyrene	0.62	96	0.161	2.39	1.0×10^{-11} [25][g]	68	0.049	0.357
PCB congeners								
PCB 105		18	<0.021	0.090				

(continued)

Table 2 (continued)

Pollutant	Preliminary remediation goals[a] (µg/g)	House dust[b] % Detected	Median (µg/g)	95th Percentile (µg/g)	Vapor pressure (kPa at [ ]°C)	Classroom dust[c] % Detected	Median (µg/g)	95th Percentile (µg/g)
PCB 138		33	<0.021	0.22				
PCB 153		40	<0.021	0.24				
PCB 170		14	<0.021	0.056				
PCB 180		26	<0.021	0.112				

[a] Smucker (2004)
[b] Usual detection limits are 0.021 µg/g for most listed pollutants; exceptions were 0.025 µg/g (methoxychlor), 0.027 µg/g (carbaryl), 0.055 µg/g (*cis*-permethrin), 0.060 µg/g (*trans*-permethrin), and 0.084 µg/g (2,4-D pentachlorophenol). Camann et al. (2002a, b), Colt et al. (2004)
[c] CARB (2003)
[d] Tomlin (2000)
[e] ATSDR (1993)
[f] Howard (1991)
[g] TOXNET (2007)
[h] Mackay et al. (1992)

at least 10 yr (PCBs, DDE, and chlordane). Considering the lack of recent use, detection of these agents in dust signified equal or greater exposure to residents for many years prior to dust sample collection. NHL risk was not found to be elevated for any of the current-use pesticides or PAHs listed in Table 2 (Colt et al. 2005, 2006; Hartge et al. 2005). Because carpet dust residues resulting from recent use are normally higher than those from the distant past and may obscure effects of aged residues, risks for cancers with a long latent period are more efficiently evaluated using dust measurements for chemicals for which there is no recent contribution.

A recent population-based case-control study in Northern California investigated risk of childhood leukemia in relation to exposure to organochlorine concentrations in HVS3-collected dust collected from carpets present in the home before the diagnosis/reference date (Ward et al. 2008). Leukemia risk was increased 2.8-fold in the highest versus lowest quartile for the sum of the six measured PCB congeners (105, 118, 138, 153, 170, 180), with a significant positive trend in leukemia risk as total PCB concentrations increased. Childhood leukemia risk was not associated with dust concentrations of chlordane, DDT, DDE, or pentachlorophenol (PCP).

The comparatively low PCB concentrations found in dust appear to be more strongly associated with incidence of both cancers (NHL and childhood leukemia) studied than are dust levels of any other semivolatile chemical measured. PCBs were used in fluorescent lighting fixtures and many other products manufactured before 1977 (ATSDR 2000), and a PCB-containing wood-floor finish, used in the 1950s and 1960s, can still be an important source of continual PCB exposure in some older homes (Rudel et al. 2008).

Seven PAHs (Table 2) have been classified as probable or known human carcinogens (IARC 1985, 2008). The frequency of detection of PAHs in carpet dust ranged from 71 to 99%, as compared with 35–77% for pesticides. The median and 95th percentile concentrations (μg/g) of chlordane and DDT, as well as five of the PAHs presented in Table 2, approached or exceeded the U.S. EPA PRGs. The median and 95th percentile concentrations of the known human carcinogen benzo(a)pyrene (BaP) exceeded the PRG (0.062 μg/g) by factors of 2.5 and 38.5, respectively (IARC 2008). The 90th percentile concentration for BaP, in Detroit house dust, was 4.8 μg/g, compared with 0.87, 0.88, and 0.21 μg/g in Iowa, Seattle, and Los Angeles, respectively (Camann et al. 2002a). The median BaP level in house dust in 120 homes on Cape Cod was 0.71 μg/g (Rudel et al. 2003).

The seven potentially carcinogenic PAHs presented in Table 2, and benzo(ghi) perylene, were detected in nearly all of the personal air samples collected from monitored pregnant minority women in New York City (Tonne et al. 2004). Prenatal exposure to these PAHs was associated with reduced fetal growth, increased risk of cognitive delay (Perera et al. 2006), and asthma (Miller et al. 2004). Chuang et al. (1999) suggest, in a pilot study, that low-income North Carolina adults received the following proportion of their exposure to PAHs that are rated by the U.S. EPA as probable human carcinogens (B_1 and B_2): diet (84%), air (9%), and dust ingestion (7%). Similarly, low-income children old enough to be toilet trained received 66% of their risk from diet, 10% from inhalation, and 24% from dust. Table 3 shows the

Table 3 Summary of PAH concentrations (μg/g) in house dust, entryway dust, and pathway soil from 24 low-income homes

Compound	House dust				Entryway dust				Pathway soil			
	Mean	Standard deviation	Minimum	Maximum	Mean	Standard deviation	Minimum	Maximum	Mean	Standard deviation	Minimum	Maximum
Naphthalene	0.33	0.85	0.02	4.30	0.11	0.26	0.01	1.31	0.01	0.01	<0.01	0.04
Acenaphthylene	0.08	0.06	0.01	0.27	0.04	0.06	<0.001	0.27	0.01	0.01	<0.001	0.03
Acenaphthene	0.05	0.04	<0.001	0.18	0.04	0.03	0.01	0.12	0.01	0.02	<0.001	0.08
Fluorene	0.12	0.24	0.02	1.22	0.04	0.03	0.01	0.06	0.01	0.01	<0.001	0.04
Phenanthrene	0.44	0.40	0.13	2.15	0.29	0.29	0.04	1.32	0.08	0.09	0.01	0.36
Anthracene	0.12	0.15	0.01	0.75	0.10	0.12	<0.001	0.40	0.03	0.05	<0.001	0.18
Fluoranthene	0.52	0.37	0.09	1.89	0.37	0.35	0.02	1.44	0.12	0.15	0.01	0.57
Pyrene	0.43	0.33	0.06	1.65	0.28	0.28	0.02	1.04	0.12	0.16	0.01	0.60
Benzo(a)anthracene[a]	0.22	0.17	0.04	0.69	0.15	0.14	0.01	0.52	0.06	0.09	<0.001	0.32
Chrysene[a]	0.39	0.47	0.05	2.41	0.20	0.19	0.02	0.74	0.02	0.02	<0.001	0.08
Cyclopenta[c,d]pyrene	0.08	0.05	0.02	0.22	0.05	0.03	<0.04	0.13	0.02	0.04	<0.001	0.20
Benzo(b and k) fluoranthenes[a]	0.55	0.32	0.17	1.34	0.36	0.28	0.04	0.08	0.12	0.15	0.01	0.47
Benzo(e)pyrene	0.26	0.17	0.05	0.75	0.20	0.15	0.02	0.54	0.05	0.06	<0.001	0.20
Benzo(a)pyrene[a]	0.23	0.15	0.07	0.63	0.15	0.13	0.01	0.41	0.06	0.01	<0.001	0.35
Indeno(1,2,3-c,d) pyrene[a]	0.23	0.18	0.05	0.70	0.16	0.13	0.01	0.42	0.05	0.07	<0.001	0.28
Dibenzol(a,h) anthracene[a]	0.10	0.09	0.02	0.41	0.05	0.05	0.01	0.15	0.02	0.03	<0.001	0.13
Benzo(g,h,i) perylene	0.25	0.16	0.08	0.61	0.17	0.13	0.01	0.37	0.05	0.06	<0.001	0.21
Coronene	0.13	0.11	0.04	0.50	0.10	0.11	0.01	0.51	0.03	0.04	<0.001	0.19
Sum of B2 PAH	1.73	1.25	0.46	5.98	1.08	0.86	0.13	2.87	0.40	0.51	0.02	1.77
Sum of target PAH	4.52	2.91	1.25	15.20	2.85	2.05	0.42	6.58	0.96	1.10	0.06	3.84

[a]Denotes B2 carcinogenic PAHs

Source: Adapted with permission from Chuang et al. (1999)

concentration of 18 PAHs in house dust, entryway dust, and pathway soil. The sum of the B_2 carcinogenic PAH concentrations in house dust exceeds four times the concentration found in the sum of the same compounds in entryway soil, which suggests preferential track-in of small particles (Roberts et al. 1996).

The low vapor pressures of the carcinogenic PAHs listed in Table 2 suggest that they will condense quickly after combustion, be deposited in soil, and be tracked into houses.

In cold climates downwind of large cities (London, New York, and Boston), where coal combusted at low temperatures has been burned for home heating, it is expected that stable PAHs such as BaP may accumulate in soil and house dust. In southeast England, the BaP in the "plow layer" (top 23 cm of soil) increased by a factor of more than 15 in the 100-yr period between 1880 and 1980; the total PAH burden in soil increased by a factor of 4. The flux rate for BaP was 0.36 mg/m^2 per year (Jones et al. 1989). Beyea et al. (2006) found a correlation between automotive traffic emissions to the air and soil concentrations of PAHs; air emissions were also correlated with the incidence of blood PAH–DNA adducts in women on Long Island, New York. They did not find a similar pattern with PAHs in house dust and suggest that indoor PAHs from cooking may have been an important source of indoor PAHs. The infant or adult diet may be the main source of PAH exposure, but the percentage of total exposure allocated to dust exposures for the carcinogenic PAHs may be three times higher (24% vs. 7%) among low-income children (Chuang et al. 1999).

The exposure of babies to BaP in house dust is worrisome, because BaP is a confirmed human carcinogen (IARC 2008) that has a possible impact on asthma and mental development (Miller et al. 2004; Perera et al. 2006). Moreover, BaP exists in up to 96% of homes, is detected at median concentrations that are 2.5 times higher than the PRG action level for residential soil at Superfund sites (Camann et al. 2002a), is persistent, and has increased its concentration in soil by a factor of 15 over a 100-yr period downwind from London (Jones et al. 1989). The largest source of BaP and other house-dust-associated toxicants may be from track-in of soil (Adgate et al. 1998; Chuang et al. 1999; Roberts and Ott 2006); this suggests that vacuuming, removal of shoes at the door, use of booties, and wiping shoes on a high-quality door mat may be good control strategies.

2.5 Phthalates

Although the health effects of infants' exposure to lead in house dust are well documented (Canfield et al. 2003; Lanphear et al. 2005; U.S. EPA 2003), less is known about infant exposures to semivolatile PAHs, phthalates, phenols, and PBDEs used as flame retardants, organotins, perfluorinated organics (PFOs), and dioxins in dust. Jones-Otazo et al. (2005), Stapleton et al. (2005), and Lorber (2008) suggest that most PBDE exposure to both children and adults comes from house dust.

Health-based PRGs have been established for residential soils at U.S. EPA Superfund sites for many EDCs such as pesticides and PAHs, but not for most phthalates, PBDEs, and PFOs, which are also EDCs (Moriwaki et al. 2003; Smucker 2004). PFOs are of particular concern because they are water soluble and difficult for humans to excrete.

Wildlife health effects are associated with exposure to EDCs that mimic or interfere with hormones, particularly the estrogen function, even though the causal link between exposure to EDCs and endocrine disruption may not be clear (Jobling and Tyler 2006). In the National Health and Nutrition Examination Survey (NHANES; 1999–2002), an association was found between abdominal obesity, insulin resistance, and several urinary phthalate metabolites in a cross section of US men (Stahlhut et al. 2007). An association was also found between a metabolite of the plasticizer DEHP (diethylhexylphthlate) in urine and reduced thyroid hormone in blood of 408 men in Boston (Meeker et al. 2007). The combined effect of EDC mixtures in house dust is unknown. A test was developed to measure the effect of mixtures of EDCs, or the total effective xenoestrogen burden, in the placenta at birth by Fernandez et al. (2007). These and other investigators suggest that the exposure to a mixture of EDCs during pregnancy may disturb the sexual development and increase the risk of hypospadias and cryptorchidism in male infants (Swan et al. 2005).

Rudel et al. (2003), in a study of 120 homes, found significant levels of EDCs in both indoor air and house dust as part of a case control breast cancer study on Cape Cod. Of 89 organic EDCs, 52 were detected in air and 66 in dust. Pesticide EDCs detected included 23 in air and 27 in dust. The most abundant EDC in indoor air was diethyl phthalate with a median concentration of 590 ng/m^3. This same phthalate was found in indoor air at a median concentration of 350 ng/m^3 in 125 Riverside, CA homes (Sheldon et al. 1992). DEHP was the most abundant EDC in house dust, in both the 120 Cape Cod homes and in 286 sampled German homes, with median concentrations of 340 and 740 μg/g, respectively (Table 4). These and other phthalates found in dust came from plasticizers and emulsifiers in plastics, food packaging, building materials, and personal care products. The concentrations detected exceeded the PRGs or other health-based guidelines for 15 compounds in air or dust, but there were no such guidelines for 28 of the 89 EDCs. In addition to endocrine and reproductive effects, phthalates have been implicated in asthma, which may be related to their ability to induce oxidative stress (Bornehag et al. 2004; Jaakkola et al. 2006; Kolarik et al. 2008).

2.6 PBDEs

A rise in Canadian and US blood and breast milk PBDE concentrations, in the 1990s and 2000s, suggests that exposure to PBDEs in house dust was increasing during this period (Stapleton et al. 2005). House dust is the source of an estimated 82% of

Table 4 Levels of PAHs, pesticides, phthalates, phenols, polybrominated diphenyl ethers (PBDEs), alkylphenols, and alkylphenol ethoxylates in house dust from 120 Cape Cod homes and 196 or 286 German homes

		Cape Cod house dust[b]			German house dust[c]	
Pollutant	Preliminary remediation goals[a] (µg/g)	% Detected	Median (µg/g)	Maximum (µg/g)	Median (µg/g)	95th Percentile (µg/g)
PAHs						
Pyrene	2,300	96	1.33	39.8		
Benz(a)anthracene	0.62	76	4.99	10.0		
Benzo(a)pyrene	0.062	85	0.712	18.1		
Pesticides					*196 Homes*	
4,4-DDT	1.7	65	0.279	9.61	0.31	4.2
Chlorpyrifos	180	18	RL[d]	228	<0.1	0.63
α Chlordane	1.6	39	RL	9.97		
Methoxychlor	310	54	0.240	12.9	0.92	27
Pentachlorophenol	3.0	86	0.793	7.96	0.95	8.0
Phthalates					*286 Homes*	
Dicyclohexyl phthalate		77	1.88	62.7		
Diethyl phthalate	49,000	89	4.98	111		
Di-*n*-butyl phthalate		98	20.1	352	49	240
Benzylbutyl phthalate	12,000	100	45.4	1,310	31	320
Di-iso-butyl phthalate		95	1.91	39.1	34	130
Diethylhexyl phthalate (DEHP)		100	340	7,700	740	2,600
Bis(2-ethylhexyl) adipate		100	5.97	391.5		
Phenols						
Bisphenol A		86	0.821	17.6	3.4	9.2
2,4-dihydroxybenzophenone		63	0.515	9.36		
PBDEs						
PBDE 47		45	RL	9.86		
PBDE 99		55	0.304	22.5		

(continued)

Table 2 (continued)

Pollutant	Preliminary remediation goals[a] (μg/g)	Cape Cod house dust[b]			German house dust[c]	
		% Detected	Median (μg/g)	Maximum (μg/g)	Median (μg/g)	95th Percentile (μg/g)
PBDE 100		20	RL	3.4		
Alkylphenols and alkylphenol ethoxylates						
4-Nonylphenol		80	2.58	8.68		
Nonylphenol monoethoxylate		86	3.36	15.6		
Nonylphenol diethoxylate		86	5.33	49.3		
Octylphenol monoethoxylate		50	0.13	1.99		
Octylphenol diethoxylate		69	0.306	2.12		

[a] U.S. EPA preliminary remediation goals (PRGs) for superfund residential soils, in ppm (Smucker 2004)
[b] Source: Rudel et al. (2003). <150 μm in diameter from thimble on vacuum wand
[c] Source: Butte and Heinzow (2002). <63 μm in diameter from occupant vacuum bags
[d] RL = reporting limit

adult PBDE exposure; the percentage is even higher for children (Lorber 2008). The estimated PBDE dose received by children 1–5 yr of age is six times higher than for adults (49.3 vs. 7.7 ng/kg/d), because of their lower body weight and higher dust intake. Lorber (2008) suggests that the higher concentration of PBDEs in blood and breast milk in the USA versus Europe is related to the tenfold higher concentrations found in US house dust. The average house dust concentrations of PBDE 47, PBDE 99, and PBDE 100 in 89 Massachusetts homes (Rudel et al. 2003) were 700, 1,290, and 170 ng/g dry mass, respectively, as compared with concentrations for the respective PBDEs in 40 German homes of 20, 180, and 20 ng/g (Stapleton et al. 2005).

Two of the three commercial PBDE mixtures, PentaBDE and OctaBDE, have been voluntarily withdrawn or banned from use in some parts of the world. However, a recent study has shown that residues of at least five of the alternative or new brominated fire retardants are showing up in Boston homes (Stapleton et al. 2008).

2.7 *Phenols and Alkylphenols*

Some phenols are also reported to be estrogenic EDCs (Rudel et al. 2003). The alkylphenols are impurities or degradation products of alkylphenol polyethoxylates used in detergents, personal care products, and as inert ingredients in pesticide formulations (Rudel et al. 2003). Table 4 shows levels of various PAHs, pesticides, phthalates, phenols, PBDEs, alkylphenols, and alkylphenol ethoxylates found in 120 house-dust samples collected from Cape Cod, four phthalates from 196 German homes, and four pesticides and bisphenol A (BPA) in a separate group of 286 German homes (Butte and Heinzow 2002; Rudel et al. 2003). The size of the house dust particles analyzed in the Cape Cod study was <150 μm in diameter, whereas particle size in the German study was <63 μm.

Wilson et al. (2007) found BPA in house dust in 25% of 119 North Carolina homes (95th percentile = 0.236 μg/g), and in 47% of 116 Ohio homes (95th percentile = 0.141 μg/g). The median values were below detectable levels. In the same study, they found PCP in house dust in 92% of 121 North Carolina homes (median 0.060 μg/g, 95th percentile 0.492 μg/g) and in 94% of 119 Ohio homes (median 0.060 μg/g, 95th percentile 0.345 μg/g). The authors analyzed children's exposure to BPA and PCP in homes and day care centers in food, outdoor air, indoor air, soil, and house dust. The potential incidence of exposure to BPA was 99% in both states, primarily from dietary ingestion. The authors estimated that the proportion of those exposed to PCP came primarily from inhalation: 78% in NC and 90% in Ohio (Wilson et al. 2007).

Camann et al. (2005) studied dust (particle size < 150 μm) taken from vacuum cleaner bags from ten homes in each of seven states (CA, MA, ME, MI, NY, OR, WA). The mean cumulative concentration of targeted EDCs found ranked by descending percent detected was as follows: five diester phthalates (mainly DEHP), 424 μg/g (90%); six alkylphenols and their ethoxylates, 26.7 μg/g (5.6%); nine pesticides, 12.7 μg/g (2.7%); six PBDEs, 9.1 μg/g (1.9%); four organotins, 0.65 μg/g (0.1%); and perfluorinated chemicals, 0.50 μg/g (0.1%).

2.8 Dust Mites, Mold, Other Allergens, Viruses, and Bacteria

Asthma rates have more than doubled in the USA since 1980, and asthma is the most common chronic illness, cause of hospitalization, and school absence of children in the USA (Akinibami 2006; Institute of Medicine 2000). Dust is both a reservoir and a vehicle that enhances human contact with asthma triggers such as dust mite allergen, mold, animal dander, cockroach and rodent allergens, PAHs, smoke deposits, and many other compounds in house dust that irritate the lungs and mucous membranes. House dust can be a trigger for asthma and allergy attacks.

There is sufficient evidence that exposure to dust mites can cause asthma in susceptible children (Institute of Medicine 2000). Sensitization of children to dust mites is one of the strongest risk factors for persistent asthma in adults (Sears et al. 2003). The highest concentration of dust mite antigen in dust is found in beds that maintain a mild temperature, contain moisture, and have a copious supply of skin scales. These conditions are optimum for dust mite growth and reproduction. When a baby or adult moves in bed and rubs against bedclothes the dust mite antigen (fecal pellets) are resuspended from the sheets or pillow and can be inhaled. The fabric in allergy control covers allow air to pass through, but the tight weave does not allow penetration of dust mites or their pellets. Although dust mites have a diameter similar to the size of a period on this page, they are rarely seen because they are transparent and flee from light (Arlian and Morgan 2003). Removal of dust from a bedroom carpet or removal of the carpet from a bedroom are important ways to reduce exposure to dust allergens (Institute of Medicine 2000). It is much easier to remove skin scales and dust mite allergens from a bare floor than from a carpet (Roberts et al. 1999).

The presence of mold in a home can double the risk of childhood asthma (Jaakkola et al. 2005). Mold commonly collects in house dust (Roberts et al. 1999). Mold and dampness can have the same large effect as does secondary tobacco smoke on child asthma, allergies, bronchitis, and other health problems, and these have a greater effect on children than on adults (Brunekreef et al. 1989; Institute of Medicine 2000). Children are more easily sensitized to environmental exposures (mold and other allergens) than are adults (Selgrade et al. 2006).

Dust is a source of bacteria (Roberts et al. 1999) and viruses in saliva and tracked-in bird, rodent, cat, and dog feces (Benson 1985; McCaustland et al. 1982). Endotoxin, produced by Gram-negative bacteria, is closely associated with asthma (Thorne et al. 2005).

2.9 Hygiene Hypothesis

Results of some studies suggest that exposure to higher levels of endotoxin from indoor Gram-negative bacteria or other infectious agents in house dust or during personal contact in early life may protect against allergen sensitization that may lead to allergies and asthma (Gereda et al. 2000; Zeldin et al. 2006).

Daily exposure to farm animals, early childhood infection from being raised in a large family, or attendance at daycare appear to protect against asthma. These observations have led to the "hygiene hypothesis," the idea that early exposure to infections may strengthen the immune system. Some families may assume that more house dust and less cleaning are good for their children. However, it was reported from a study of 4,000 school-aged children in Southern California that exposure during the first year of life to wood or oil smoke, cockroaches, herbicides or other pesticides, farm dust, or farm animals was associated with prospects for an asthma diagnosis before age 5 (Salam et al. 2003). In addition, some risk factors for asthma such as respiratory viral infections, obesity, pesticide exposure, and living in an inner-city community do not fit with the hygiene hypothesis (Zeldin et al. 2006).

There are serious flaws in the concept of exposing infants and others to low doses of pollutants in hopes of stimulating a protective response (Thayer et al. 2005). Exposing children to PAHs or other carcinogens, pesticides, endocrine disruptors, and neurotoxins that coexist with allergens in house dust cannot be justified by the hygiene hypothesis. It is prudent to reduce infant exposure to house dust by appropriate house cleaning and hand washing, while continuing to search for a safe method for protecting babies against sensitization to allergens.

3 Cleaning Practices, Carpets, and Safer Cleaning Products

3.1 Cleaning

Effective cleaning of homes and buildings can reduce dust and indoor air exposures to particles, lead, bacteria, allergens, and other pollutants (Franke et al. 1997; Gereda et al. 2000; Krieger et al. 2005; Lioy 2006; Roberts 2007). Cleaning helps protect the health of infants and adults. Effective home cleaning also encompasses preventive measures such as removing shoes at the entrance door to better control dust track-in. Other effective measures include providing commercial-grade door mats and regularly monitoring and extracting removable dust from carpets, plush furniture, bare floors, and other surfaces (Roberts 2007). Effective cleaning also improves indoor air quality. A year-long study, designed to measure the benefits of cleaning, in a large day care center (without any known indoor air problems) reduced indoor airborne dust by 58%, and total bacteria, Gram-negative bacteria, and fungi (mold) by 40%, 88%, and 61%, respectively (Franke et al. 1997). These pollutant levels were measured for 5 mon before and 7 mon after the cleaning program was introduced. More frequent and thorough cleaning is required in damp and warm climates to control dust and bacterial growth, dust mites, and mold that utilize the moisture and nutrients in dust to grow. Higher levels of cleaning are also required in houses built before 1978, when lead was phased out of paint; special attention is needed for houses built before 1940 because higher lead levels are normally present.

Most pollutants in dust are tracked in from outdoors (Adgate et al. 1998). Preventing dust track-in is easier than removing dust from a carpet. Shoe removal at the entrance is the best way to prevent track-in; simply wiping one's feet twice on a high-quality door mat may be 75% as effective as shoe removal (Roberts et al. 1991b). Commercial-grade door mats such as the "Twister" mat, used at many store entrances, are effective. However, such mats cost two to three times as much as most home door mats and are difficult to find in retail stores. They can be specially ordered at large hardware stores or purchased from commercial mat companies found in the yellow pages.

3.2 Carpets and Alternatives

Some carpets are much easier to clean than others. Flat and level loop carpets, often found in office buildings, are the easiest to clean. Short plush carpets are the next easiest to clean. Deep plush and shag carpets are the most difficult to clean. Spilled liquids may initiate mold growth in or under a carpet (without a water barrier on the pad) that is not dried within 24 hr. In 2005, the cost of installing a Powerbond carpet in Seattle was $3.50/ft^2. In 2008, the cost of installing alternative floor coverings in Seattle was as follows (per square foot): Berber carpet $1–$4, wood laminate $6–$8, tile $9–$11, and hardwood $8–$12. Wood laminate floors are popular but are not advertised as waterproof.

Carpets have advantages in reducing noise, are softer to walk and crawl on, may reduce the severity of falls, and have a lower cost than bare floors. Throw rugs and small area rugs present a hazard on bare floors and are a source of falls for both children and adults (Braun 2003). Larger carpets can provide greater traction than bare floors and may reduce injury in the event of a fall (Bunterngchit et al. 2000; Maki and Fernie 1990). However, replacing carpets with bare wood floors reduces cleaning time and also reduces exposure to dust and associated pollutants found in carpets and carpet backing. Older carpets tend to have more dust and health risks (Kim and Ferguson 1993; Roberts and Ott 2006). Hardwood and tile floors are more expensive than carpets, but last longer. Replacing carpets is usually not an option for most people who rent, but they can improve cleaning and hand washing. They can remove deep dust by using a vacuum cleaner with a dirt detector that electronically affirms when all removable dust has been vacuumed.

Plush furniture collects dust in the same way that plush carpets do and must be cleaned with a vacuum cleaner attachment or hand vacuum cleaner that has a rotating brush. Covering plush furniture with a washable fabric cover is one way to reduce exposure to accumulated dust.

3.3 Vacuum Cleaners

The carpets found in most homes collect dust and pollutants as they age (Kim and Ferguson 1993; Roberts et al. 1991a, 1999, 2004). Normal vacuuming removes surface dust but allows deep dust to accumulate, which may become surface and airborne dust after activity on the carpet (Roberts and Ott 2006). The total removable dust in a carpet is the sum of the surface and extractable deep dust. In two studies, the total removable dust (median 26.3 and 63.2 g/m^2, respectively) in samples of Seattle carpets more than 10-yr old exceeded the surface dust (median 1.3 and 2.9 g/m^2) by a factor of 20 or more (Roberts et al. 1999, 2004). Less than 20% of the lead, PAHs, and pesticides are usually found in the dust that can be extracted from older carpets by vacuuming, whereas, more than 80% of lead and 90% of PAHs and pesticides remain in the carpet fibers, backing, and pad (Roberts and Dickey 1995; U.S. EPA 2000). Pollutants with a higher vapor pressure (including chlorpyrifos, diazinon, and some PAHs) are unlikely to be removed from carpets by cleaning; these pollutants may continue to degrade indoor air quality and be deposited on room surfaces (Lioy 2006; U.S. EPA 2000). The source of the persistent concentrations of chlorpyrifos in indoor air, following many air exchanges, could not be explained until this large source was discovered.

The development of vacuum cleaners fitted with dirt sensors improved cleaning performance, because these units indicate when dust is still being collected from a carpet; such sensors allow monitoring of the effectiveness of extracting removable dust from a carpet. A Hoover vacuum cleaner, equipped with a dirt finder sensor using red and green indicator lights, was used to develop a standard "three-spot test method" to estimate the deep dust content and the time to remove it from a carpet (Roberts et al. 2004).

The three-spot test provides a measure of the time (in seconds) for the vacuum cleaner indicator lights to turn from red to green, when three locations are vacuumed 3 ft apart and at least 4 ft from an entrance door. The vacuum cleaner is held motionless on each spot until the light turns green. Achieving three green lights in less than 11 sec indicates that the carpet is relatively clean and retains less than 10 g/m^2 of removable dust. If the three-spot test takes 40 sec, the carpet may contain 80 g/m^2 of removable dust. A time of 6 sec on the three-spot test is an achievable goal. In contrast, a clean bare floor passes the three-spot test in less than 1 sec, with green light showing immediately everywhere. In most cases, the three-spot test can be performed in 1 min by families and professional cleaners to determine when the carpet is clean and all the removable dust has been extracted.

When deep dust was removed from 10-yr old carpets in daily use, the surface dust was reduced by 84–99% (measured 1 wk later with the HVS3; Roberts et al. 2004). Camann and Buckley (1994) collected data from 362 Midwest homes and estimated the median loading of surface dust on sampled carpets to be 1.4 g/m^2. This loading level can be reduced to less than 0.1 g/m^2, when deep dust is removed (Roberts et al. 2004).

The three-spot test correlates with, and gives a better indication of the total removable dust than does measuring surface dust (Roberts et al. 2004). Performing a walk-through survey and questionnaire by a trained outreach worker and conducting a three-spot test for dust in carpets is a low cost and efficient way to monitor dust and other exposures in a home (Roberts and Ott 2006).

Not all vacuum cleaners are equally effective. A canister vacuum cleaner without a power head can allow up to 400 g/m^2 of removable dust to collect in area rugs or plush carpets. Vacuum cleaners that utilize a power brush are two to six times more effective in carpet cleaning than are those without this device. A vacuum cleaner with a power head removes approximately 35–55% of added dust from a plush carpet and 70–80% from a flat or level loop carpet (personal communication: John Balough, The Hoover Company, 1988). The canister cleaner without a power head removes only 4% of resident dust from a shag rug, 10% from a plush carpet, and 40–50% from flat carpets. Ten to 25 times as much dust, lead, pesticides, and other pollutants may remain in an old rug than is removed by normal vacuuming (Roberts et al. 1999, 2004; U.S. EPA 2000).

Nearly any type of vacuum cleaner will remove all dust from a bare floor and is far superior to cleaning (sweeping) with a broom. Brooms may cause more particles to become airborne while leaving many particles behind. Wet mopping with a detergent and rinsing will help remove soot from a bare floor and is an option for poor families, who cannot afford a working vacuum cleaner. Area rugs on bare floors act as magnets for dust and should be cleaned by vacuuming with a power brush. It takes longer to clean a rug near entrance doors and in high-traffic areas because there is more dust to remove. If all the removable deep dust is not vacuumed from a carpet, in approximately 5% of cases, one may end up with more dust and pollutants on the carpet surface than was originally present (Roberts and Ott 2006). Vacuuming in two perpendicular directions may reduce the time required to get the green light on the dirt finder (personal communication: Debra Tucker, The Hoover Company, 2003). Vacuum cleaners will not work effectively if the bag is full and if the belt or brush is worn or broken. Bags should be changed when they are half full. When vacuum cleaners are not maintained, they lose their effectiveness and should be serviced.

Dusting with a damp cloth is one of the best ways to clean furniture, walls, and woodwork. Dusting should be done after vacuuming to remove any dust stirred up by this activity. The cloth must be changed or cleaned every 10 min, depending on how much dust is present, to maintain efficiency. Once the removable deep dust is vacuumed from the carpet, less dust will accumulate and be visible on woodwork and other surfaces.

Annual hot water-extraction cleaning of carpets helps to restore color and remove the soot that clings to carpet fibers that cannot be removed by vacuuming. Shampooing carpets with a detergent is often used to remove soot and stains, but increases the risk for mold unless the carpet and pad dry within 24 hr. Detergent residues left in the carpet after shampooing may contain pollutants. Hot water extraction does not require use of any detergent. Wet vacuuming is not as effective as dry vacuuming in removing dust (Lewis 2002). Removal of deep dust by dry vacuuming prior to commercial truck-mounted hot water extraction (or steam cleaning) provides one option for restoring color to a carpet, with less chance of leaving a damp carpet, dust, or increased surface lead. An all-purpose detergent is recommended for removing lead from surfaces (Lewis et al. 2006). Sending area rugs to a professional cleaner that features inversion, beating, vacuuming, immersion in a detergent solution, and rinsing is expensive but may remove pollutants that would otherwise remain in the fibers and backing.

3.4 Hand Washing

Hand washing with soap and water or with an alcohol-based fluid is the best way to stop the spread of infectious diseases and prevent transfer of pollutants in dust from surfaces to hands, food, mouth, and eyes. Hand sanitizing is widely used by the Group Health medical facilities in the Northwest USA. It has been found to be effective in both hospitals and homes, partly because it is more convenient and much quicker for busy parents and medical personnel (Sandora et al. 2005). Hand washing can reduce the 3.5 million annual deaths of children that result from diarrhea and acute lower respiratory tract infections (Luby et al. 2005; Nenstiel et al. 1997). Infectious diseases are the leading cause of death worldwide, and the third leading cause of death in the USA. Such diseases are also a leading cause of childhood illness (Nenstiel et al. 1997). Because infants are more vulnerable to infectious disease and ten times more vulnerable to pollutants on dust than are adults (U.S. EPA 2003), they have the most to gain from caregiver hand washing. Under normal circumstances, using regular soap without antimicrobial ingredients should be sufficient (Larson et al. 2004).

Infants can be protected by caring adults, who wash a baby's hands often, and who wash their own hands after cleaning, changing a diaper, sneezing into their hands, gardening, or going to the bathroom, and before preparing food, eating, or handling a baby (Luby et al. 2005). Supplying the infant with a clean pacifier is a good way to reduce finger sucking and the associated ingestion of dust and bacteria. Frequent washing of toys or other objects that a child puts in its mouth and putting a clean sheet down before you put an infant on the carpet also reduces dust and bacteria exposure. Good personal hygiene that includes hand washing, clean clothes, and effective house cleaning is a proven way to protect workers and infants exposed to dust contaminated with lead, arsenic, and other pollutants (OSHA, 1987; Davies et al. 1990).

3.5 Safer Cleaning Products

While cleaning the home is important, the choice of cleaning products and safe storage of them are also necessary to protect children's health. Cleaning products are frequently involved in home exposures reported to poison centers, with children under the age of 6 representing about half of all cases (Watson et al. 2005). In 2004, the percentage of moderate to major health outcomes, including death, reported from exposure to corrosive products was 14.03% (alkali drain cleaners), 14.33% (alkali oven cleaners), 11.14% (hydrofluoric acid rust removers), and 8.30% (acid toilet bowl cleaners). In comparison, for all other cleaning products, the percentage was only 3.56%. Corrosive products can be easily identified by the presence of the signal word "Danger" on product labels, in conjunction with the word "corrosive." A few solvent-based cleaning products such as furniture polishes and metal polishes also carry a “Danger” signal word because of their aspiration hazard if ingested. Sodium hypochlorite and ammonia are respiratory irritants, and products containing sufficient concentrations of these ingredients can irritate the lungs when used with inadequate ventilation. Strong respiratory irritants can also be produced if hypochlorite is mixed with ammonia or strong acids.

Choosing the least-toxic cleaning (and pest control) product to use in the home is difficult. This is because few ingredients are listed on product labels, and label warnings are primarily oriented toward acute exposures (Dickey 2005). Avoiding products with “Danger” or “Poison” signal words, in favor of those with “Caution” or no signal words, can remove the most acutely toxic products from homes, but does not guarantee that all ingredients are benign. All cleaning products should be securely stored out of reach of children.

4 Reducing Exposure and Health Costs with Home Visits

Environmental exposures are associated with increased rates of disease and health costs. Reducing exposures, when combined with health-improving behaviors, has the potential to reduce health costs by more than 30% (Eyre et al. 2004; Louis et al. 2007). Incentives are being used to improve health-related behaviors and can be used to reduce exposures of infants. Resources used to protect infants from exposures may have a much greater impact on health costs, learning, and productivity than the same resources used to protect older people, because babies are more vulnerable to exposures (U.S. EPA 2003). Such differences can be taken into account when doing exposure analysis (Ott 2006).

4.1 Home Surveys

The Home Environmental Assessment List (HEAL™©) used in the MHE Program of the American Lung Association of Washington (ALAW), together with the three-spot test mentioned previously, is a cost-effective way to develop a family action plan to reduce dust and total infant exposure. The MHE program helps people reduce their exposures to dust and indoor air by using trained volunteers to do a walk-through survey in the home with a family member Dickey (2007). Some 65 questions are asked that relate to exposures in the home, which helps the family establish priorities for improvement. The topic areas covered in the training and HEAL™© include lead, dust, indoor air, mold, moisture, biological contaminants, household chemicals, ventilation, tobacco cessation, asthma, allergies, and behavior change. At the end of the HEAL™© survey the family and the volunteer negotiate the top three actions the family is willing to do within 6 wk. Volunteers make a follow-up phone call after 2 wk to answer any questions and to reinforce the suggested changes.

The MHE program has spread from the ALAW of Seattle to Tacoma, WA; Yakima, WA; Wenatchee, WA; Colville, WA; Okanagan, WA; Olympia, WA;

Portland, OR; Boise, ID; New York, NY; Washington, DC; Fresno, CA; San Jose, CA; Bismark, ND; Providence, RI; San Antonio, TX; and Tulsa, OK. More than 800 volunteers have been trained in Seattle as of May 2008.

Although information is essential to induce families to make the changes required to reduce indoor exposures in a timely manner, it is insufficient when used alone (Krieger et al. 2005; Wu and Takaro 2007). Other factors that may help an individual or family make permanent changes include home surveys, support from a doctor, nurse, outreach worker, or friend. Laws and regulations that reduce environmental emissions and exposures to lead and other pollutants, in outside air, have little effect on in-home exposures that require changes in cleaning methods, home maintenance, ventilation, and use of consumer products. The role of MHEs in home exposures may, therefore, have a favorable impact. Trained MHEs and community health workers (CHWs) can reach where regulations cannot. MHEs can give motivational interviews that empower a family by meeting their unique needs and advise them on many low or no cost actions a family can take to improve cleaning, hand washing, ventilation, and selection of home chemicals.

Taking action to create a healthier home will provide important gains in comfort, productivity, and quality of life. Those individuals and families who suffer from asthma and allergies, or who are concerned about the indoor risks to babies and sensitive individuals, will be most willing to seek help in assessing and controlling indoor exposures. Other sensitive groups are the elderly, those ill with cancer, heart disease, AIDS, and poor immune systems, or those who have “sick-building”-associated health problems.

4.2 Reducing Asthma and Health Costs

Leung et al. (1997) and Primomo et al. (2006) have evaluated the effectiveness of the MHE program in Seattle and Tacoma, respectively. Leung found changes in family cleaning behavior after a home assessment by a MHE. Primomo found that 60 of 64 families (94%) made at least one change in cleaning behavior. Also, 34 out of 39 families (or 87%) with an asthmatic member reported an improvement in the condition of the sufferer after a HEAL™ evaluation and changes to cleaning behavior. The HEAL™ evaluation, by a trained community volunteer, is an effective way to increase knowledge about the home environment, asthma, and allergy triggers. Families who evaluate their home situation with a HEAL™ assessment tend to engage in behavioral changes and perceive improvements in asthma and allergy symptoms. Improvement in dust control is one of the most frequent changes after a HEAL™ assessment (personal communication: Maruyama, ALAW, 2005).

As part of the Seattle-King County Healthy Home Project I, Krieger et al. (2005) evaluated the benefit of environmental intervention by CHWs in reducing exposure to asthma triggers in the homes of 274 low-income asthmatic children. The families in the high-intensity group were given allergy control bedding covers, vacuum cleaners (with a dirt finder), high-quality doormats, and cleaning kits.

The Hoover Company provided the premium vacuum cleaners at cost, but such vacuum cleaners could be purchased at retail for $125, in 2008. The CHWs made five to nine visits over 1 yr focusing on asthma trigger reduction. The three-spot test (Roberts et al. 2004) was used to evaluate the effectiveness of carpet dust control and was performed at the beginning and end of the program. In 74 homes for which data were available, the average time to get three green lights on the dirt finder-equipped vacuum cleaners dropped 61%, from 59 to 23 sec, and the median time dropped 23%, from 15 to 11.5 s (Takaro et al. 2004). This test was attractive to both the CHWs and caregivers because it could be performed in less than 1 min, tended to reinforce effective cleaning, and the client could see immediate results.

Krieger et al. (2005) also documented reductions in exposures to asthma triggers, the severity of asthma, and health care costs. This trial was randomized and controlled and designed to compare results of a "high-intensity" intervention (multivisits and equipment used) with that of a "lower intensity" intervention (single visit, no special equipment used). In the higher intensity group, the incidence of nighttime symptoms, during a 2-wk period, dropped from 4.5 to 0.9 (80%); the incidence of daytime symptoms dropped from 8.1 to 3.4 (58%) and that of daytime symptoms with activity limitations dropped from 5.6 to 1.5 (73%). The proportion of participants using urgent health care services (unscheduled doctor visits and the emergency room) dropped by 15%. There was also a reduction in the use of medicines. The frequency of missed school days dropped from 31.1% to 12.1%. The percent of parents who missed work dropped from 13.1% to 11.2%. There was a significant improvement in the quality of life of the caregiver as measured by the Juniper Scale (Juniper et al. 1996).

The program cost per high intensity client was $1,345/yr, with an estimated annual medical care savings of $1,205–$2,001. This project also reduced the total exposure of the children to lead, pesticides, EDCs, and carcinogens as well as asthma triggers in dust. The lower intensity group received only allergy control mattress and pillow covers, plus one visit, at an annual cost of $222, and savings of $1,050 to $1,786, annually. This study did not collect follow-up data on both groups, but utilization of urgent care remained low among the high-intensity group for at least 6 months following the intervention. If one assumes this lower cost of urgent care, observed 6 mon after exit among the high-intensity group, persisted for 4 yr, the high-intensity intervention would be less costly, relative to the low-intensity intervention. The savings per child, discounted at 3%/yr, would range from $1,316 to $1,849 for 4 yr. Wu and Takaro (2007) demonstrated the cost-effectiveness of using a combination of environmental interventions including the use of CHWs for childhood asthma.

In 2007, the Washington State Legislature approved funding to help 700 low-income Medicaid children in King County, who had moderate to severe asthma, over a period of 4 yr. The same methods described by Krieger et al. (2005) will be used and are expected to cost $789 per child, with up to three home visits from trained CHWs, who will be supervised by nurses and doctors. Savings in health costs averaging $2,200 per child per year are estimated and result from fewer visits to hospitals, emergency rooms, and doctors. Standards for selection, training, and supervision of CHWs can be developed or adjusted to aid in the transfer of this program to the 38,000 other children in the Washington State or to the large number of children in the entire USA who have poorly controlled (moderate to severe) asthma (Dilley et al. 2005). It is estimated that 33% of Medicaid children with this level of asthma severity are less than 6 yr of age (personal communication: J. Krieger, 2007). The integrated home visits designed to improve the asthma and early learning of this large group of low-income children can be financed in part by the reduction in medical costs. Such children are expected to miss fewer days of school. They will be able to play, learn, work, and live better with less asthma.

The National Cooperative Inner-City Asthma Study (NCICAS) of 1,033 low-income asthmatic children was performed in Seattle and seven other cities (Morgan et al. 2004). These children were given allergy control pillow and mattress covers and the family provided education and social support in controlling asthma triggers in the home. NCICAS also reported a reduction in asthma severity. This study found that it was cost-effective to spend an average of $245 per year per child to achieve a $9.20 saving per symptom-free day gained. The sicker the child the greater the health cost savings. Managing exposure to asthma triggers, rather than the associated disease, could result in important social and financial benefits (Sullivan et al. 2002; Kattan et al. 2005).

Other studies also show the benefit of home remediation to reduce asthma triggers (Wu and Takaro 2007; Kercsmar et al. 2006). As more people become aware of this information, it is likely that families will ask for more assistance to reduce their everyday exposure to pollutants. Government as well as public and private groups have an important role to play in disseminating these research findings to the public on how to reduce their exposure, risks, and costs. Involving the community in planning and at the start of an environmental intervention has many advantages (Krieger et al. 2005). However, some investigators have reported disappointing results (Thompson et al. 2008; McCauley et al. 2006), suggesting that much remains to be learned regarding community-based interventions.

Giving low-income families access to an effective vacuum cleaner removes a major source of environmental discrimination by increasing their ability to remove house dust (Krieger et al. 2005). Twenty-five percent of the families in the Seattle study did not have a vacuum cleaner at the beginning of the study; perhaps another 25% of homes did not have functioning vacuum cleaners, because they had full bags, worn or broken belts, air leaks, or worn agitators. The average surface dust loading, from the Seattle study, dropped from 2.64 to 0.96 g/m^2 after cleaning (Takaro et al. 2004). This compares favorably with the 1.4 g/m^2 median loading measured in 272 Midwest homes in the childhood leukemia study (Camann and Buckley 1994). The dust loading in both studies was measured with the HVS3. There is still room for improvement. A surface loading of 0.1 g/m^2 can be achieved when the removable deep dust is extracted (Roberts et al. 1999, 2004). Low-income families with asthmatic children, who live in substandard housing, may be exposed to hazards in addition to dust such as leaky roofs and plumbing, mold, pest intrusion, poor ventilation and temperature control, deteriorated paint, environmental tobacco smoke, poor access to medical care and food, crime, as well as stress related to complex social problems (Wu et al. 2007). The CHWs are trained to help such families deal with urgent difficulties that present barriers to reducing exposure to asthma triggers in the home.

5 Discussion

It is easy for families who receive home visits to monitor deep dust in carpets with the three-spot test. It may take 10–30 min of cleaning each day for a week to reduce dust-related risks by a factor of 10–100. Most families, with support of the local health department, health maintenance organization, and family doctor can take simple steps to reduce the exposure of infants to dust. Effective cleaning methods such as using an improved vacuum cleaner with higher efficiency dirt pickup and filtration, as well as a dirt finder, when combined with curtailing track-in of dirt may also save time. Even though there are many scientific uncertainties about the risks and health effects of dust exposure, it may be best to take the precautionary approach that emphasizes prevention and protection of children. It has also been argued that we have an ethical obligation to protect infants who have no political power and cannot protect themselves (Gilbert 2005).

Many pollutants get into house dust by migrating from consumer and household goods. Removing the most toxic compounds from consumer products is an important and necessary step in reducing exposure. However, it may be decades after a pollutant such as DDT, chlordane, or lead is banned, before it disappears from soil, food, indoor air, house dust, and carpets. A family can take action now, with improved cleaning and hand washing, to reduce a significant fraction of an infant's total exposure to allergens, lead, PBDEs, and other pollutants, by reducing contact with toxic compounds in house dust. This can provide an immediate reduction in exposure and enhances the large benefit of removing pollutants from consumer products, or emission and exposure reductions achieved by passage of the Clean Air Act of 1970 or other environmental laws that followed. These laws have reduced outdoor exposures and partially reduced indoor exposures and have reduced the rate at which pollutants build up in soil.

Additional cleaning is needed to protect babies with pica, because they tend to consume more dust. Effective cleaning and hand washing will also help protect people in several different situations: infants and toddlers living in old houses, where they may face risks of high-lead exposure; residents in areas where soil is contaminated by traffic (Beyea et al. 2006); those near Superfund sites; or near sources of other industrial emissions. It is estimated that 400,000 children (2% of children aged 5 or under) have ingested sufficient lead to cause learning disabilities or behavioral and gastrointestinal problems (CDC 2007; Markel 2007).

Replacing older carpets with the newer short-fiber impermeable ones appears to offer many advantages for reducing exposures. For many families, this is a more affordable option than installing bare floors. Some commercial carpets used in green hospitals come with low volatile organic emissions, are waterproof, 100% recyclable, easier to clean, and are free from PVCs (polyvinylchlorides), phthalates, and PBDEs, which are found in many older carpets (Walsh 2006).

Monitoring pollutant levels and setting standards for exposures have brought large benefits to workers. A similar effort would also benefit children. The cancer rates for US children increased by 26% from 1975 to 1998, with mortality rates falling by approximately 40%, because of improved treatments (U.S. EPA 2003), whereas the cancer mortality rate for US workers fell by 50% as a result of increased monitoring and control of carcinogen exposures (Trichopoulos et al. 1996). Asthma rates for children doubled since 1980 (Akinibami 2006), while occupational asthma from exposure to detergent dust was reduced as a result of monitoring and control efforts (Cathart et al. 1997). Monitoring and analysis of total exposure is necessary to efficiently manage health risks, disease, and costs associated with infants, workers, and adults (Ott 2006).

6 Research Recommendations

This review provides a basis for hypotheses that warrant future research:

1. The cost of home visits by CHWs or MHEs to reduce exposure to asthma triggers for children with poorly controlled asthma can be recovered in 1 yr or less in reduced medical costs.
2. The rates of childhood and adult asthma, and cancer, can be reduced by home interventions that reduce the total exposure of infants.
3. The percentage of children with chronic illness, including asthma and ADHD, can be reduced by home interventions that reduce the total exposure of infants to dust and other sources of pollutants.
4. Home visits will help families reduce dust exposures in the home by 90% in 1 wk, at a cost less than $160.
5. Home visits can be used to improve hand washing for families of infants.
6. Improved cleaning and hand washing can reduce the lead and PBDEs levels in infants, children, and adults.
7. Improved cleaning and hand washing can reduce the incidence of infections.

The National Children's Study (NCS) of 100,000 children over 21 yr (http://www.nationalchildrensstudy.gov/) offers an opportunity to test hypotheses 2, 3, 5, 6, and 7. A select group of the NCS children can serve as a control group for a matched intervention group.

7 Summary

The health risks to babies from pollutants in house dust may be 100 times greater than for adults. The young ingest more dust and are up to ten times more vulnerable to such exposures. House dust is the main exposure source for infants to allergens, lead, and PBDEs, as well as a major source of exposure to pesticides, PAHs, Gram-negative bacteria, arsenic, cadmium, chromium, phthalates, phenols, and other EDCs, mutagens, and carcinogens. Median or upper percentile concentrations in house dust of lead and several pesticides and PAHs may exceed health-based standards in North America.

Early contact with pollutants among the very young is associated with higher rates of chronic illness such as asthma, loss of intelligence, ADHD, and cancer in children and adults. The potential of infants, who live in areas with soil contaminated by automotive and industrial emissions, can be given more protection by improved home cleaning and hand washing. Babies who live in houses built before 1978 have a prospective need for protection against lead exposures; homes built before 1940 have even higher lead exposure risks. The concentration of pollutants in house dust may be 2–32 times higher than that found in the soil near a house.

Reducing infant exposures, at this critical time in their development, may reduce lifetime health costs, improve early learning, and increase adult productivity. Some interventions show a very rapid payback. Two large studies provide evidence that home visits to reduce the exposure of children with poorly controlled asthma triggers may return more than 100% on investment in 1 yr in reduced health costs. The tools provided to families during home visits, designed to reduce dust exposures, included vacuum cleaners with dirt finders and HEPA filtration, allergy control bedding covers, high-quality door mats, and HEPA air filters.

Infants receive their highest exposure to pollutants in dust at home, where they spend the most time, and where the family has the most mitigation control. Normal vacuum cleaning allows deep dust to build up in carpets where it can be brought to the surface and become airborne as a result of activity on the carpet. Vacuums with dirt finders allow families to use the three-spot test to monitor deep dust, which can reinforce good cleaning habits. Motivated families that receive home visits from trained outreach workers can monitor and reduce dust exposures by 90% or more in 1 wk. The cost of such visits is low considering the reduction of risks achieved. Improved home cleaning is one of the first results observed among families who receive home visits from MHEs and CHWs. We believe that proven intervention methods can reduce the exposure of infants to pollutants in house dust, while recognizing that much remains to be learned about improving the effectiveness of such methods.

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